Abstract. The calculations of the p-process in the O/Ne layers of Type II supernovae are quite successful in reproducung the solar system content of p-nuclides. They predict, however, a significant underproduction of the rare odd-odd nuclide ^{138}La. A model for the explosion of a 25 $M_\odot$ star with solar metallicity is used to suggest that ν_e-captures on ^{138}Ba may well be its most efficient production mechanism. The responsibility of an inadequate prediction of the ^{138}La and ^{139}La photodisintegration rates in the too low production of ^{138}La is also examined quantitatively. A detailed discussion of the theoretical uncertainties in these rates suggest that the required rate changes are probably too high to be fully plausible. Their measurement would be most welcome. They would help disentangling the relative contributions of thermonuclear and neutrino processes to the ^{138}La production.

Key words: nuclear reactions, nucleosynthesis – solar system: general

A&A manuscript no.
(will be inserted by hand later)

Your thesaurus codes are:
missing; you have not inserted them

ASTRONOMY
AND
ASTROPHYSICS

The puzzle of the synthesis of the rare nuclide ^{138}La

S. Goriely, M. Arnould, I. Borzov and M. Rayet

Institut d'Astronomie et d'Astrophysique, Université Libre de Bruxelles, CP 226, B-1050 Brussels, Belgium

Received date; accepted date

1. Introduction

The odd-odd neutron-deficient heavy nuclides ^{138}La and isomeric ^{180}Ta^m are among the rarest solar system species (no information exists for other locations), with ^{138}La/^{139}La $\approx 10^{-3}$ and ^{180}Ta^m/^{181}Ta $\approx 10^{-4}$. In spite of their scarcity, their origin has long been a puzzle. As initially claimed by Prantzos et al. (1990) and confirmed by Rayet et al. (1995; hereafter RAHPN), ^{180}Ta^m appears to be a natural product of the p-process in the O/Ne-rich layers of Type II supernovae (SNII). In contrast, ^{138}La is underproduced in all p-process calculations performed so far (e.g. Fig. 1 of Arnould et al. 2001).

In view of the low ^{138}La abundance, it has been attempted to explain its production by non-thermonuclear processes involving either stellar energetic particles (Audouze 1970) or neutral current neutrino-induced transmutations (Woosley et al. 1990). The former mechanism is predicted not to be efficient enough, while the latter is found by Woosley et al. (1990) to be able to overproduce the solar ^{138}La/^{139}La ratio by a factor of about 50. This prediction has to be taken with some care, however, especially in view of the qualitative nature of the evaluation.

In a one-dimensional $Z = Z_\odot$ $M = 25$ M$_\odot$ SNII model, ^{138}La is predicted to be produced only at peak temperatures around $2.4 \pm 0.1 \times 10^9$ K (Arnould et al. 2001) from a subtle balance between its main production by ^{139}La$\,(\gamma\,,\mathrm{n})\,^{138}$La and its main destruction by ^{138}La$\,(\gamma\,,\mathrm{n})\,^{137}$La. The resulting abundances cannot account for the solar system ^{138}La amount. The same conclusion holds for all the stars in the $13 \leq M/\mathrm{M}_\odot \leq 25$ examined by RAHPN. This situation might of course just result from inadequate astrophysics and/or nuclear physics inputs. On the astrophysics side, one might incriminate an uncertain prediction of the evolution of the thermodynamic conditions of the ^{138}La producing layers during the explosion. Modifying these conditions is unlikely, however, to cure the ^{138}La underproduction. For any astrophysically plausible conditions, the SNII layers releasing the highest ^{138}La yields are also those overproducing even more significantly heavier p-nuclides as ^{156}Dy, ^{162}Er or ^{168}Yb. Of course, it remains to be seen if the situation could be drastically modified if multi-dimensional effects were duly taken into account. On the nuclear physics side, one has to be aware of the fact that the ^{138}La yield predictions rely entirely on theoretical nuclear reaction rates. One is thus entitled to wonder about the sensitivity of the computed ^{138}La underproduction to the nuclear uncertainties that affect the production and destruction channels. One of our aims is to provide the first quantitative examination of this question (see also Arnould et al. 2001).

Our second aim is to analyse on more quantitative grounds than Woosley et al. (1990) the possibility of producing ^{138}La at a level compatible with the solar system abundances through neutrino nucleosynthesis (ν-process). To this end, the same $M = 25$ M$_\odot$ SN model as considered above is selected. The RAHPN p-process network is augmented with the neutrino and anti-neutrino charged-current inelastic scatterings off the network nuclei, and with the neutrino neutral current inelastic scatterings off the Ba, La and Ce isotopes.

Section 2 analyses the purely thermonuclear p-process production of ^{138}La. A brief description of the adopted astrophysical model and input nuclear physics is followed by the evaluation of the impact on the calculated ^{138}La yields of changes in the ^{139}La$\,(\gamma\,,\mathrm{n})\,^{138}$La and ^{138}La$\,(\gamma\,,\mathrm{n})\,^{137}$La rates. We also examine the plausibility of the rate modifications that are needed in order to avoid an unsatisfactory ^{138}La underproduction. The neutrino nucleosynthesis contribution to the p-nuclides, and in particular to ^{138}La, is discussed in Sect. 3. Conclusions are drawn in Sect. 4.

2. ^{138}La and the p-process

The p-process calculations reported here are based on a model for a $Z_\odot$ 8 M$_\odot$ helium star (main sequence mass of about 25 M$_\odot$) already considered by RAHPN. It is evolved from the beginning of core He burning to SN explosion (for details, see Hashimoto 1995). We consider here as P-Process Layers (PPLs) 25 O/Ne-rich zones with explosion temperatures peaking in the (1.7-3.3)$\times 10^9$ K range. Their total mass is approximately 0.75 M$_\odot$. The deepest PPL is located at a mass of about 1.94 M$_\odot$, which is far enough

from the mass cut for all the nuclides produced in this region to be ejected during the explosion.

The abundances of the s-process seeds for the production of the p-nuclides are calculated with the NACRE 'adopted' $^{22}\mathrm{Ne}\,(\alpha\,,\mathrm{n})\,^{25}\mathrm{Mg}$ rate (Angulo et al. 1999), as described by Costa et al. (2000; see the distribution labelled R_1 in their Fig. 2).

The p-process reaction network includes some 2500 stable and neutron-deficient nuclides with $Z \leq 84$. The n-, p- and α-capture reactions on all nuclei are considered, as well as their (γ,n), (γ,p) and (γ,α) photodisintegrations. The nuclear reaction rates are the NACRE 'adopted' ones for charged particle captures by nuclei up to ^{28}Si (Angulo et al. 1999). For heavier targets, the rates predicted by the latest version of the Hauser-Feshbach code MOST (Goriely 2001) are adopted (the NACRE and MOST rates are available in the Brussels Nuclear Astrophysics Library http://www-astro.ulb.ac.be). This version benefits in particular from an improved description of the nuclear ground state properties derived from the microscopic Hartree-Fock method (Goriely et al. 2001), as well as from a more reliable nuclear level density prescription based on the microscopic statistical model (Demetriou & Goriely 2001). Finally, the experimentally-based neutron capture rates of Bao et al. (2000) are used.

As in RAHPN, the computed abundance of the p-nuclide i produced in the PPLs of the $Z_\odot$ 25 M$_\odot$ star considered here is represented by its mean overproduction factor $\langle F_i \rangle = \langle X_i \rangle / X_{i,\odot}$, where $X_{i,\odot}$ is its solar mass fraction (Anders & Grevesse 1989), and

$$\langle X_i \rangle = \frac{1}{M_p} \sum_{n\geq 1} (X_{i,n} + X_{i,n-1})(M_n - M_{n-1})/2, \qquad (1)$$

where $X_{i,n}$ is the mass fraction of isotope i at the mass coordinate M_n, $M_p = \sum_{n\geq 1}(M_n - M_{n-1})$ is the total mass of the PPLs, the sum running over all the PPLs ($n = 1$ corresponds to the bottom layer). An overproduction factor averaged over all 35 p-nuclei is calculated as $F_0 = \sum_i \langle F_i \rangle /35$, and is a measure of the global p-nuclide enrichment in the PPLs. So, if the computed abundances were exactly solar, $\langle F_i \rangle / F_0$ would be equal to unity for all i. Fig. 1 indicates that most of these factors lie in the 0.3 to 3 range. The cases for which an underproduction is found are discussed by RAHPN or by Costa et al. (2000) for ^{92,94}Mo and ^{96,98}Ru. Only the ^{138}La problem is tackled here.

We turn our special attention to the impact of alterations in the MOST rates for $^{137}\mathrm{La}\,(\mathrm{n}\,,\gamma)\,^{138}\mathrm{La}$ and $^{138}\mathrm{La}\,(\mathrm{n}\,,\gamma)\,^{139}\mathrm{La}$. The Maxwellian-averaged cross sections at $T = 2.5\ 10^9$ K are predicted to be 123 and 62 mbarn, respectively. These are used to calculate the reverse ^{138}La and ^{139}La photodisintegrations of direct interest in the ^{138}La production by the application of the detailed balance theorem. More specifically, we examine the extent to which the rate of $^{137}\mathrm{La}\,(\mathrm{n}\,,\gamma)\,^{138}\mathrm{La}$ has to be *decreased* and the one of $^{138}\mathrm{La}\,(\mathrm{n}\,,\gamma)\,^{139}\mathrm{La}$ *increased* in

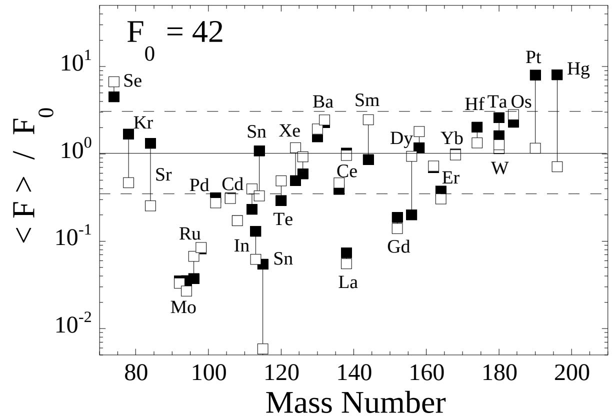

Fig. 1. Normalised p-nuclide overproduction factors $\langle F_i \rangle / F_0$ ($F_0 = 42$) obtained for the $Z = Z_\odot$ 25 M$_\odot$ model star with the nominal MOST rates and in absence of neutrino nucleosynthesis (open squares). For comparison, black squares designate the factors calculated by RAHPN with the use of a different set of nuclear reaction rates. The dotted horizontal lines delineate the $0.3 \leq \langle F_i \rangle / F_0 \leq 3$ range.

order to bring the ^{138}La overproduction at levels comparable with those of the neighbouring p-nuclides. In the following, the factors of decrease and increase will be noted F_{down} and F_{up}, respectively. The corresponding reverse photodisintegration rates are decreased and increased by the same factors. In our numerical tests, F_{down} and F_{up} are selected to vary independently in the 1 to 10 range.

Fig. 2 shows the ratio $R_{138} = \langle F(^{138}\mathrm{Ce}) \rangle / \langle F(^{138}\mathrm{La}) \rangle$ obtained in this test. The choice of ^{138}Ce as the normalizing p-nuclide is dictated by the fact that it is produced in an amount close to the average value F_0, so that R_{138} gives a good representation of the ^{138}La production by the p-process. It is seen that R_{138} is pushed inside the $0.3 \leq \langle F \rangle / F_0 \leq 3$ range represented in Fig. 1 only for $F_{\mathrm{down}} \times F_{\mathrm{up}} \approx 20$ to 25. It remains to be seen if such changes are physically plausible.

Many of the input data necessary to calculate reaction rates with MOST have been measured for ^{139}La. This concerns in particular giant dipole energies and widths, or the neutron resonance spacings. In contrast, very little is known experimentally for ^{137}La or ^{138}La, so that their predicted neutron capture rates are likely to be less reliable. In order to evaluate the rate uncertainties, a series of calculations have been performed with values of some basic input quantities differing from their nominal values to an extent which is considered as reasonable (in view of the trends and systematics for neighbouring nuclei). Of course, the compatibility with the experimental constraints, if any, is always imposed.

This analysis clearly demonstrates that the main sources of uncertainties lie in the nuclear level densities, γ-ray strength functions and neutron optical potentials. Related errors in the capture rate predictions can amount to

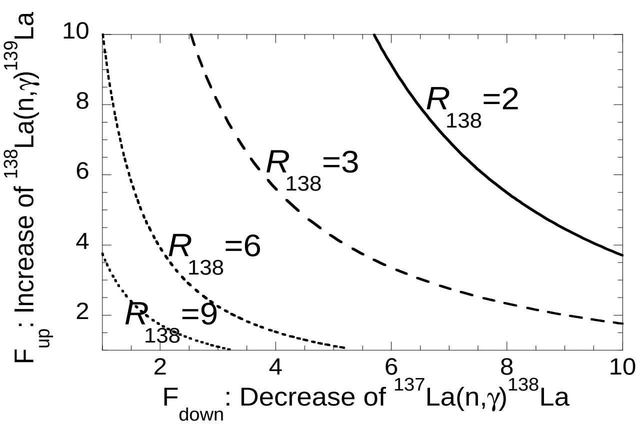

Fig. 2. ^{138}Ce to ^{138}La overproduction ratio, R_{138}, for different values of $F_{\rm down}$ and $F_{\rm up}$.

about a factor of 2 for ^{138}La(n,γ)^{139}La at the temperature of relevance (2.4 10^9 K) for the ^{138}La synthesis. In view of scarcer experimental information, larger uncertainties affect the ^{137}La(n,γ)^{138}La rate. Even so, it is unlikely that the product $F_{\rm down} \times F_{\rm up}$ introduced above can realistically reach the requested value of about 20 to 25 in order for the underproduction of ^{138}La with respect to ^{138}Ce not to exceed a factor of 3 (see Fig. 2). Of course, only experimental determinations of the ^{138}La and ^{139}La photodisintegration rates could really put this theoretical conclusion on a safe footing. Such experiments are feasible today (Vogt et al. 2001) and are strongly encouraged.

3. The production of ^{138}La by neutrino captures

The calculations of Sect. 2 neglect the irradiation of the PPLs by the neutrinos streaming out of the proto-neutron star. In order to examine the impact of the neutrino interactions on the p-nuclide yields, and in particular on ^{138}La, the reaction network used in Sect. 2 is augmented with all neutrino-induced reactions (charged and neutral currents) up to Kr (all rates are from Hoffman & Woosley 1992), as well as all charged-current neutrino and antineutrino scatterings up to Po. The neutral-current scatterings off nuclei heavier than Kr are considered only for the Ba, La and Ce isotopes.

The neutrino and antineutrino scattering cross sections are averaged over supernova (anti)neutrino spectra that are approximated by zero-degeneracy Fermi-Dirac distributions corresponding to typical temperatures $T_\nu = 8, 5$ and 4 MeV for the ν_x (where x stands for μ and τ (anti)neutrinos), $\bar{\nu}_e$ and ν_e, respectively (Fuller & Meyer 1995). The allowed transitions for the charged-current (anti)neutrino scatterings are treated fully microscopically within the cQRPA approximation (Borzov et al. 1995, Borzov & Goriely 2000) and on grounds of the ETFSI ground state description (Aboussir et al. 1995). The Gamow-Teller (GT) strength function accounts for the transitions to the daughter nucleus ground and low-lying states, to the GT resonance (GTR) and to the particle continuum region above the GTR. The entire $(N-Z)$ Fermi strength is contained in the isobaric analog resonance (IAR), its energy being taken from the experimental systematics of Coulomb displacement energies. It has to be noted that the IAR and GTR usually appear as decay states for $N < Z$ nuclei. In such conditions, $\bar{\nu}$-captures dominate ν-captures (the situation is the reverse in $N > Z$ nuclei, where the IAR and the main part of the GT strength are excited via ν-capture).

As the average $\nu_e(\bar{\nu}_e)$ energies are low ($E < 16$ MeV), allowed transitions are expected to dominate the scattering processes. For nuclei in the neighbourhood of ^{138}La, we just take into account the contribution from the forbidden transitions in a very rough way through the increase by 25% of the microscopically calculated $\nu(\bar{\nu})$-capture cross sections for allowed transitions (Hektor et al. 2000). In particular, the resulting averaged ν_e-capture cross section by ^{138}Ba is estimated to be 7.5 10^{-41} cm^2 at $T_{\nu_e} = 4$ MeV. The neutral current ν-scattering contribution is also estimated in a rough way by assuming an approximate scaling of the $(\nu_x, \nu_{x\prime})$ cross section with mass number. At $T_{\nu_x} = 8$ MeV, the excitation cross section followed by neutron emission of the La isotopes is 1.2 10^{-41} cm^2.

The energy-integrated number flux of neutrinos of type ν at a radius r_7 (expressed in units of 100 km) is estimated in terms of the neutrino-sphere radius and temperature T_ν and of the ν-neutrino luminosity L_ν to be (Fuller & Meyer 1995)

$$\Phi_\nu = 1.58 \times 10^{41}\ {\rm cm}^{-2}\ {\rm s}^{-1} (\frac{L_\nu}{10^{51} {\rm ergs\ s}^{-1}})\ (\frac{\rm MeV}{kT_\nu})\ \frac{1}{r_7^2}. \quad (2)$$

In this expression, L_ν is assumed to vary between about 10^{51} and 10^{52} ergs s^{-1}. This quite broad range of values is selected in order to accomodate to the many intricacies and uncertainties in the detailed neutrino fluxes emanating during the whole nucleosynthesis episode from the nascent neutron star underlying the O/Ne-rich zones of interest here. Note that Φ_ν [Eq. (2)] depends on r_7, which varies with time in all the considered layers. Let us also emphasize that no oscillation between neutrino species is taken into account. Would ν_e's be converted to heavier species by matter-induced oscillations, larger $\nu(\bar{\nu})$-capture cross sections on bare nuclei could be expected (mainly due to the contribution of forbidden transitions).[1]

Fig. 3 shows the impact of the neutrino interactions on the p-nuclide production for the two sets of typical luminosities (Fuller & Meyer 1995) $L_\nu[10^{51}$ ergs s$^{-1}] = (3,$ 4, 16) and (30, 40, 160) for ($\nu_e, \bar{\nu}_e$ and ν_x). These two L_ν combinations lead to increases of the ^{138}La production with respect to the case without neutrinos by factors

[1] This work was completed by the time the SNO collaboration has announced that their neutrino data were supporting the existence of neutrino oscillations (Giles 2001). A quantitative analysis of the impact of this exciting discovery on the ν-synthesis of ^{138}La has clearly to be postponed

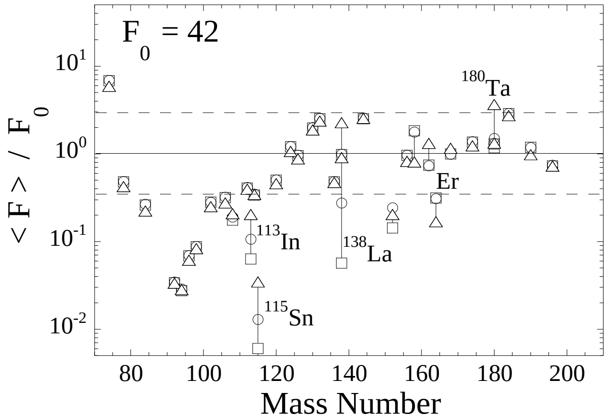

Fig. 3. Comparison of the p-process abundances obtained with and without (squares) neutrino interactions (with standard MOST rates). Two sets of luminosities $L_\nu[10^{51}$ ergs s$^{-1}]$ =(3, 4, 16) (circles) and (30, 40, 160) for $(\nu_e, \bar{\nu}_e, \nu_x)$(triangles) are adopted for the calculations with neutrinos.

of 4.8 and 36, respectively. This enhanced synthesis originates entirely from the ν_e-capture by ^{138}Ba, the neutral current scatterings on ^{139}La being found to have a negligible impact. Despite relatively similar cross sections, the ^{138}Ba ν_e-capture is found particularly efficient due to the large initial ^{138}Ba abundance (about 10 times the ^{139}La abundance). For the high luminosity set, the ν_e-captures also enhance the production of ^{113}In, ^{115}Sn, ^{162}Er and ^{180}Ta. Despite the numerous uncertainties still affecting supernova models and the neutrino physics in supernovae (spectra, luminosity, temperature, oscillation, interaction cross sections, ...), ν_e-captures appear so far to be the most efficient production mechanism of the solar ^{138}La.

4. Conclusions

Woosley et al. (1990) have considered as an 'intriguing possibility' the production of ^{138}La by (charged current) ν_e-captures on ^{138}Ba. We provide the first quantitative support to this possibility through the use of a 'realistic' one-dimensional SNII model and of an extended network of nuclear and neutrino reactions the rates of which benefit from a series of improvements. Still, astrophysics and nuclear/neutrino physics uncertainties remain and forbid this conclusion to be as strong as one might want.

The responsibility of an inadequate prediction of the ^{138}La$(\gamma, n)^{137}$La and ^{139}La$(\gamma, n)^{138}$La photodisintegration rates in the too low production of ^{138}La is also examined quantitatively. Clearly, a suitable ^{138}La production could be obtained by adequate changes in the nominal rates. However, it is concluded from a detailed study of the theoretical uncertainties in these rates that the level of the required changes is probably too high to be fully plausible. An experimental study of the above-mentioned key rates is no longer out of reach and is eagerly awaited. These measurements would certainly help greatly disentangling the relative thermonuclear and neutrino synthesis contributions to one of the rarest nuclides in nature.

Acknowledgements. S.G. and M.R. are FNRS research associates

References

Aboussir Y., Pearson J.M., Dutta A.K., Tondeur F., 1995, At. Data Nucl. Data Tables, 61, 127

Anders E., Grevesse N., 1989, Geochim. Cosmochim. Acta, 53, 197

Angulo C., Arnould M, Rayet M. & the NACRE Collaboration, 1999, Nucl. Phys., A 656, 3

Arnould M., Goriely S., Rayet M., 2001, in Cosmic Evolution, eds. E. Vangioni-Flam et al. (Singapore: World Scientific), in press

Audouze J., 1970, A&A, 8, 436

Bao Z.Y., Beer H., Käppeler F. et al., 2000, At. Data Nucl. Data Tables, 76, 70

Borzov I.N., Goriely S., 2000, Phys.Rev., C62, 035501

Borzov I.N., Fayans S.A., Trykov E.L., 1995, Nucl. Phys., A584, 335

Costa V, Rayet M, Zappalà R.A., Arnould M, 2000, A&A, 358, L67

Demetriou P., Goriely S., 2001, Nucl. Phys., A in press.

Fuller G.M., Meyer B. S., 1995, ApJ, 453, 792

Giles J., 2001, Nature 411, 877

Goriely S., 2001, in Tours Symposium on Nuclear Physics III, AIP Conf. Proc. 561, eds. M. Arnould et al. (New York: AIP), 53; *http://www-astro.ulb.ac.be*

Goriely S., Tondeur F., Pearson J.M., 2001, At. Data Nucl. Data Tables 77, 311

Hashimoto M., 1995, Progr. Theor. Phys. 94, 663

Hektor A., Kolbe E., Langanke K., Toivanen J., 2000, Phys. Rev., C61, 055803

Hoffman R.D., Woosley S.E., 1992, *http://ie.lbl.gov/astro.html*

Prantzos N., Hashimoto M., Rayet M., Arnould M., 1990, A&A, 238, 455

Rayet M., Arnould M., Hashimoto M., Prantzos N., Nomoto K., 1995, A&A, 298, 517 (RAHPN)

Vogt K., Mohr P., Babilon M. et al., 2001, Phys. Rev., C 63, 055802.

Woosley S.E., Hartmann D.H., Hoffman R.D., Haxton W.C., 1990, ApJ, 356, 272